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THE BUILDING OF ATOMS AND THE NEW PERIODIC SYSTEM[1]

WHAT is usually known as the periodic system of the elements was developed largely in the decade from 1860 to 1870, during the period of our civil war, by de Chancourtois, Newlands, Mendeléeff and Meyer. Mendeléeff, the third to develop the system, has been given almost all of the credit for it, but this is largely because he paid very much more attention to its details than any of the three others. It has now been found that the Mendeléeff periodic relation is simply one method of expressing the arrangement in space of the electrons in the outer part of the various kinds of atoms.

Five years ago I discovered a *new periodic system of the elements, or more properly speaking, of the atoms. This second system is not at all directly related to the arrangement of the electrons in the outer part of the atom, but has been found to indicate how the atoms are built up, that is, it is related to the structure of the nuclei of the different species of atoms.*

In order to understand the meaning of this new periodic system it is important to have a good idea of the present theory as to the general structure of the atom. According to Rutherford the atom is similar to the solar system in that it has a central sun called the nucleus of the atom, and a system of planets, each of which consists of one negative electron. The atom as a whole is electrically neutral, and the electrons outside the nucleus, which we may call the planetary electrons, are held in the atom by a positive charge on the nucleus. This positive charge is equal numerically to the sum of the charges of all of the planetary electrons. This is often expressed

[1] Abstract of a general address presented at the Philadelphia meeting of the American Chemical Society, September 3, 1919.

by the statement that the number of positive charges on the nucleus is equal to the number of negative electrons, since it is known that the hydrogen ion carries a positive charge equal to the negative charge on the negative electron.

The atom is similar to the solar system in a second sense, for the planetary electrons are, relative to their size, about as far from each other and from the nucleus, as the planets and the sun. Thus it need not be surprising from this point of view, that Rutherford has found that the very minute nucleus of a helium atom, often called the alpha particle, may be shot directly through many thousands of other atoms, without hitting a single nucleus or a single negative electron, just as a planet like the earth might be shot through thousands of solar systems like our own without hitting a single sun or planet.

The atom is like the solar system too, in that the nucleus, like the sun, possesses nearly the entire mass of the system, since in general the nucleus is more than two thousand times heavier than all of the electrons which surround it. While the atom is so small that a row of fifty million atoms would be only about one inch long, if they were put as closely together as they are in solids; and so small too, that there are 180 thousand billion billion atoms of carbon in one cubic centimeter of diamond; the atom is so *large* compared with the electron, that, if we take the dimensions usually accepted for the electron, there would be space in a single atom sufficient to contain ten million billion electrons, while the atom which contains the greatest number of planetary electrons, uranium, actually has only 92 of these. According to the work of Rutherford, Geiger, Darwin and Marsden, the nucleus of even the heaviest atom, is not very much larger than a negative electron. Thus the atom may be said to be very sparsely populated with electrons.

The atom is *unlike* the solar system in that the planetary electrons are arranged more or less symmetrically in space around the nucleus, at least that is the idea expressed in papers by the American chemists, Parsons, Harkins, Lewis and Langmuir, the last two having paid the most attention to the details of the arrangement. Also, while the solar system is held together by the gravitational attraction between the large mass in the sun and the smaller masses in the planets, the atoms are held together by the positive electrical charges in the nucleus and the negative charges of the electrons, together with whatever magnetic effects are produced by the rotation of the electrons.

THE BUILDING OF ATOMS

While chemists have not as yet synthesized any atoms, it is also true that they have only recently begun the study of their structure. Now, when a chemist wishes to build up even such a simple thing as an organic molecule, he first studies its structure, and often many years intervene between the working out of the structure of the molecule and its first synthesis. In the synthesis of an organic dye there may be two steps which we may have to consider. Suppose for example that the first of these consists of a complex set of reactions which are very difficult to carry out, while the second step will occur by itself if the intermediate product is only left standing in the air. It is evident that the practical chemist will need to put almost his whole attention on the first step of the synthesis. The building of atoms is similar in that the first step, the building of the nucleus of an atom, has not yet been accomplished, while, if the nucleus were once built, it would of itself pick up the whole system of planetary electrons which would turn it into a complete atom. For example in the disintegration of the nuclei of certain radioactive atoms, alpha particles which are the nuclei of helium atoms, are shot out as rapidly as twenty thousand miles per second, so rapidly that they pass through as many as *half a million* other atoms before coming to comparative rest. Now Rutherford has proved that when these nuclei finally slow down, they give the ordinary spectrum of helium, which indicates that each alpha particle has picked up the two negative electrons which are essential to convert it into a complete helium atom.

THE BUILDING OF THE NUCLEI OF COMPLEX ATOMS

Suppose that we consider the specific problem of the building of a carbon atom. The characteristic chemical and physical behavior of carbon are due to its six planetary negative electrons, and these will arrange themselves around any nucleus which carries a positive charge of six, so our problem reduces to that of putting six positive charges of electricity into the extremely minute space occupied by the nucleus of an atom, with a diameter of the order of 10^{-12} cm., that is one millionth of a millionth of a centimeter. These six positive charges must not only be put into this *ultra-ultra-microscopic* space, but must unite to form an intra-nuclear compound of extreme stability.

Now, up to the present time, the smallest mass ever found associated with one positive electrical charge, is that of the hydrogen ion, which is associated primarily with the mass of the hydrogen nucleus, with a value of 1.0078.[2] If six of these hydrogen nuclei could be packed tightly enough together to form the nucleus of a new atom they would form the nucleus of a carbon atom, which would have a mass of approximately six. That no carbon atom of this mass exists, is not because such a nucleus if formed, would not give a true carbon atom, but because six positive hydrogen nuclei undoubtedly repel each other, and can not be made to form a stable system.

In order to make a complex nucleus stable it is necessary to include not only hydrogen nuclei, but also negative electrons. Since the mass of the ordinary carbon atom is 12.00, it could be built up from 12 hydrogen nuclei, bound together by six negative electrons. Such a nucleus would have a positive charge of 6, it would therefore take up six negative electrons, and would thus form a complete carbon atom. The only objection to this idea is that 12 times 1.0078 is 12.036, while the weight, and probably the mass, of the carbon atom is only 12.005, or the actual carbon atom is 0.76 per cent. lighter than it should be if built from 12 hydrogen nuclei without any resulting change of mass. Now Professor A. C. Lunn has worked out the mathematical expression for this effect for the writer, and this shows that according to the electromagnetic theory, if such a nucleus is held together in a very small space by attractive forces there *should* be a loss of mass in its formation, and that in a simple atom the observed loss of mass would result if the center of the negative electron has a distance 400 times the radius of the positive electron.

The alpha particle, or the nucleus of a helium atom, carries two positive charges, has a mass of four, and is probably made up of four positive hydrogen nuclei bound together by two negative electrons into what is probably by far the most stable nucleus of any known atom, except that of hydrogen itself.

If we make the atomic number of the element equal to the positive charge on the nucleus, then the atomic number of hydrogen would be one, that of helium two, that of carbon six, of lead eighty-two, and of uranium, ninety-two. Now the mass of the carbon atom (atomic number 6) is exactly what it should be if its nucleus consists of 3 alpha particles. Also, 3 times the charge on the alpha particle is just the charge on the carbon nucleus. It is easily seen that there is a possibility that the carbon nucleus is simply a compound made up of 3 alpha particles, of a formula 3 α. Now it is obvious that if the nuclei of complex atoms were simply structures built up from alpha particles, that, since the positive charge on the alpha particle is two, there would be no nuclei with an odd number of charges. The work of Mosely indicates, however, that the elements of odd atomic number also exist, but it is certain that the nuclei of such odd numbered atoms can not be compounds made of alpha particles alone.

On the other hand, it is quite evident, as I announced four years ago, that the nuclei of the atoms of even atomic number are mostly intra-nuclear compounds of helium nuclei. For this there is much evidence which will be found in my printed papers in the *Journal* of the American Chemical Society and in Science. This evidence can only be hinted at here, since the time for the paper is short,

[2] Equal to 1.66×10^{-24} grams.

TABLE I

The Helium—H_3 System of Atomic Structure $H = 1.0078$

$He = (4\ H) = 4.00$

	1	2	3	4	5	6	7	0	8	
At. No...	3	4	5	6	7	8	9	10		
	Li	Be	B	C	N	O	F	Ne		
Ser. 2 ...	$He+H_3$	$2He+H$	$2He+H_3$	3He	$3He+H_2$	4He	$4He+H_3$	5He		
Theor....	7.00	9.0	11.0	12.00	14.00	16.00	19.00	20.0		
Det......	6.94	9.1	11.0	12.00	14.01	16.00	19.00	20.0		
At. No...	11	12	13	14	15	16	17	18		
	Na	Mg	Al	Si	P	S	Cl	A		
Ser. 3 ...	$5He+H_3$	6He	$6He+H_3$	7He	$7He+H_3$	8He	$8He+H_3$	10He		
Theor....	23.0	24.00	27.0	28.0	31.00	32.00	35.00	40.0		
Det......	23.0	24.32	27.1	28.3	31.02	32.07	35.46	39.9		
At. No...	19	20	21	22	23	24	25		26	27
	K	Ca	Sc	Ti	V	Cr	Mn		Fe	Co
Ser. 4 ...	$9He+H_3$	10He	11He	12He	$12He+H_3$	13He	$13He+H_3$		14He	$14He+H_3$
Theor....	39.00	40.00	44.0	48.0	51.0	52.0	55.00		56.00	59.00
Det......	39.10	40.07	44.1	48.1	51.0	52.0	54.93		55.84	58.97

Increment from Series 2 to Series 3 = 4He. Increment from Series 3 to Series 4 = 5 He (4 He for K and Ca). Increment from Series 4 to Series 5 = 6He.

Note: The simple helium system begins with carbon (= 3 He), and continues with oxygen (4 He), neon (5 He), magnesium (6 He), silicon (7 He), sulphur (8 He), argon (10 He), calcium (10 He), titanium (12 He), chromium (13 and iron (14 He).

While both the argon and the calcium atom are built from 10 helium atoms, the nucleus of the argon atom contains 10 alpha (α) particles alone, while the nucleus of the calcium atom contains 10 alpha particles with two negative electrons which serve to bind on one of the alpha particles. These may be called binding electrons.

The composition of the thorium nucleus is expressed by the formula $\alpha_{58}e_{26}$, that of the nucleus of the uranium atom by $\alpha_{58}h_2e_{28}$, and that of the isotope of lead which comes from radium as $\alpha_{51}h_2e_{22}$.

and I wish to show just a little as to the way in which these alpha particles are bound together.

First, the atomic weights of the lighter atoms of *even* atomic number beginning with carbon are, 12, 16, 20, 24, 28, 32, 40, 40, 48, 52 and 56, the last being the atomic weight of iron, of atomic number 26. Thus the atomic weights of the atoms whose nuclear charge is expressed by an even number, are divisible by 4, the weight of the helium nucleus. If we study the elements of high atomic number, beginning with uranium, which is number 92, we find that the even numbered atoms change into the atom of next lower even number by the loss of a single alpha particle from the nucleus of the atom. Thus we find just the same system of structure indicated by the actual disintegration of the radioactive atoms, as is made evident by the atomic weights and the nuclear charges on the atoms of low atomic weight.

Second, the atomic weights of the elements of odd atomic number point to the idea that their nuclei are compounds of a certain number of alpha particles with three hydrogen nuclei, so that their formula is $n\alpha + 3h$ In the exceptional cases of nitrogen the formula is $3\alpha + 2h + \epsilon$.

Four years ago I presented the following formula for the respective nuclei:

$$\text{Carbon nucleus} = 3\alpha$$
$$\text{Nitrogen nucleus} = 3\alpha + 2h + \epsilon$$
$$\text{Oxygen nucleus} = 4\alpha$$

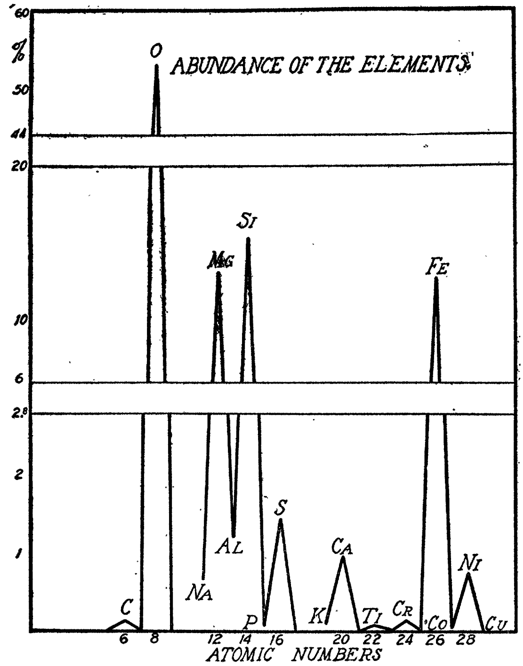
where ϵ represents a negative electron.

It is of extreme interest in this connection to note that Sir Ernest Rutherford has just announced that he has been able to bombard these atoms with extremely rapid moving alpha particles, and that he has been

able to drive hydrogen out of nitrogen atoms, but not out of either carbon or oxygen.

THE NEW PERIODIC SYSTEM OF THE ATOMIC NUCLEI

The *ordinary* periodic system, when put in a graphic form, as has been done by Crookes and more correctly by Soddy, and by Harkins and Hall, is a graphic expression of the arrangement of the planetary electrons. The *new* periodic system of the atomic nuclei was discovered by me five years ago in the following way. I reasoned that if the nuclei of the even numbered atoms are built of helium nuclei alone, while those of odd atomic number contain hydrogen nuclei in addition, that there should be a considerable difference in stability between the two classes of nuclei. I also told my students, before making any further study, that the even numbered atoms would prove to be more stable than the odd numbered.



Percentage by Atoms
Atomic Number

FIG. 1. The Periodic Variation in the Abundance of the Elements as the result of Atomic Evolution. The data are given for 350 stone and 10 iron meteorites, but the relations are true for meteorites in general. Note that *ten* elements of even atomic number makes up 97.59 per cent. of the meteorites, and *seven* odd-numbered elements, 2.41 per cent., or 100 per cent. in all. Elements of atomic number greater than 29 are present only in traces.

Now there is, unfortunately, no known method of testing directly the stability of the lighter atoms, but it seemed a reasonable hypothesis that if the atomic nuclei had ever been built up, that in general the most stable nuclei would be formed in the greatest abundance. An investigation brought forth the following facts:

1. The *atoms of the even numbered or helium series* are *127 times more abundant* in the iron meteorites than the atoms of the helium-hydrogen or odd numbered series.
2. In the stone meteorites they are 47 times more abundant.
3. In the surface of the earth the even numbered atoms are about 10 times more abundant than the odd numbered.
4. The even numbered rare earth elements are much more abundant than the odd numbered.
5. In the meteorites every even numbered element is much more abundant than the two adjacent odd numbered elements.
6. All of the seven most abundant elements in the meteorites are even numbered, and these seven elements alone make up 98.6 per cent. of all of the material of the meteorites.

Thus the periodicity of this system is from even to odd, or the periods are two atomic species in length, while in the Mendeléeff system the periods are 2, 8, 18, and 32 elements in length. Dr. Norris F. Hall, of Harvard University, has pointed out that both the isotopic complexity and the number of predominant radiators in a pleiad, follow just this periodic variation.

THE STABILITY OF THE NUCLEI OF ATOMS

The most stable nuclei seem to be those of oxygen, magnesium, silicon, iron, all of them even numbered elements of low atomic number (except that as has been stated the helium nucleus is probably extremely more stable than any of these).

The atoms whose nuclei carry 28 or less positive charges are much more stable than those of higher atomic number. This is illustrated by the relative abundance of such elements as represented by the following table:

TABLE II

Proportion in Various Materials of the Elements of Low Atomic Numbers

Material	Percentage of Elements with Atomic Numbers 1–29	30–92
Meteorites as a whole	99.99	0.01
Stone meteorites	99.98	0.01
Iron meteorites	100.00	0.0
Igneous rocks	99.85	0.15
Shale	99.95	0.05
Sandstone	99.95	0.15
Lithosphere	99.85	0.15

When there are several varieties of atomic nuclei all carrying the same positive charge, as is the case with lead, with 82 positive charges on the nucleus, the nuclei differ in stability, but the complete atoms do not differ in their chemical properties nor in their spectrum. This has been shown very beautifully by Soddy, by Merton, and by Richards and Baxter, but most accurately by Dr. Aronberg, who worked at my suggestion. Two isotopes may have practically the same atomic weights, and differ only in the stability of their nuclei, as I pointed out four years ago.

THE BUILDING OF ATOM NUCLEI AGAIN

Let us now pay attention to the building of nuclei of even numbered charge, since the time is not sufficient to consider those of odd number also. Three, four, five, six, seven, eight or ten alpha particles may unite to form the nucleus of a complex atom, but two alpha particles alone, or more than ten alone, do not make a stable system.

In all heavier atoms there are some alpha particles which are bound on by two negative electrons. Thus the sulphur nucleus is a compound of 8 alpha particles alone, while the argon nucleus contains 10 alpha particles and two negative binding electrons. It is the presence of an extra alpha particle in the argon nucleus which makes its atomic weight higher than that of potassium.

The number of binding electrons does not increase to 4 until element 32 (germanium) is reached, but rises to 26 in the thorium atom. *It is these binding electrons which are given off in the beta disintegrations of the radioactive elements,* and if time permitted it could be shown that this disintegration is exactly in accord with the system of structure proposed for the nuclei of the lighter atoms. For example a radioactive atom may lose five alpha particles in direct succession, but never more than two of the binding electrons. Furthermore, if it loses a single binding electron it always loses a second one, but not more than two, which indicates that, corresponding to our theory, such binding electrons are associated in pairs.

The principal difficulty to be encountered in the artificial disintegration of atoms, that is, in the disintegration of their nuclei, is that of getting sufficient energy into such a small volume as that of a nucleus. In the building of atoms there is the additional difficulty of securing the proper arrangement of the alpha particles to give stability.[3]

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THE DISRUPTION OF ATOMS BY ALPHA RAYS

RECENTLY under the modest title "An Anomalous Effect in Nitrogen,"[1] Rutherford reported the remarkable discovery that when nitrogen molecules are bombarded by alpha rays, penetrating rays with a range of 28 cm. in air are produced which are certainly lighter than nitrogen atoms and which are probably

[3] The details of the system of atom building presented here may be found in the following references: *Journal of the American Chemical Society,* 37, 1367–1421, 1915, 38, 186–214, 1916, 39, 856–879, 1917; 41, 970–992, 1919. *Phil. Mag.,* 30, 723–734, 1915. SCIENCE, N. S., 46, 419–427, 443–448, 1917. *Proc. National Academy of Sciences,* 1, 276, 1915; 2, 216–224, 1916.

[1] *Phil. Mag.,* 37, 581–87, June, 1919; *cf.* SCIENCE, 50, 472, November 21, 1919.